General Analysis of Anti-Deuteron Dark Matter Search

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Outline

Search Paths for Dark Matter

Existence of DM ✓– Macroscopic effects: galaxy rotation curve, gravitational lensing...

What is DM? Microscopic feature?–Little is known...

Familiar search Paths:

- Direct Detection: DM scatters off target nucleus, better control/estimation of background✓ (CDMS, XENON...) But rate may be highly suppressed: current bound SI elastic $\sigma_{\chi p} \lesssim 10^{-7}\mathrm{pb}$ for $10 - 100\mathrm{GeV}$ DM, could get more stringent in coming years (XENON100/1T, Super-CDMS)
- Indirect Detection: Cosmic Ray SM particles produced from DM annihilation, s-wave annihilation $\langle \sigma_{ann} v \rangle_{thermal} = 1\mathrm{pb}$✓ (Ω_{DM}) But most IdDt channels $(e^+, \gamma, \bar{p})$: large astrophysical bkg, uncertainties, hard to 'confirm' as DM origin (e.g.controversies after PAMELA, FERMI excess)

Low Background Channel for IdDt?$\Rightarrow$Low energy $\bar{D}$!
(Bottino, Donato, Fornengo and Salati, 1998)

- Conventional DM: color multiplicity$\rightarrow$significant BR(ann) to hadrons ('Conservative' about PAMELA excess).
  Advantages compared with $\bar{p}$:
- Higher threshold energy for *secondary* astrophysical production: $(pH), (pH_e)$ collision, $E_{th}(\bar{p}) = 7\mathrm{m_p}$, $E_{th}(\bar{D}) = 17\mathrm{m_p}$, suppression from cosmic ray p number distribution $N_p \sim E_p^{-2.7}$. $K_{\bar{D}} \sim 2\mathrm{GeV}$
- Suppressed *tertiary* production of low E $\bar{D}$: 'slow-down' during inelastic scattering off galactic nucleus: $\bar{p}$✓, Not for $\bar{D}$! 'Fragility': $E_{binding}(\bar{D}) = 2.2\mathrm{MeV}$$\Rightarrow$ Breaking apart instead of losing energy

High sensitivity experiments coming soon!
–AMS-02 (2010), GAPS (LDB2011, ULDB2014, SAT)

Our Goal

Most existing anti-D related DM study: signal for particular DM models, e.g. SUSY $\tilde{\chi}_0$ (Donato, Fornengo, Salati, 1999; Baer and Profumo 2005, etc.)

Our goal: Take a broader view– $+$general analysis for general DM candidates

- Anti-D flux from various SM final states, mass reach at AMS-02, GAPS
- Generic scalar, fermion, vector DM models: correlation between thermal relic density, DiDt and IdDt, operator analysis

Injection Spectrum

- $\bar{D}$ injection spectrum: m_{DM}, final states composition ($\bar{t}t$, $\bar{b}b$, $h^0 h^0$, gg, $W^+ W^-$)
  –hadronization simulated by PYTHIA6.4
- Formation of $\bar{D}$ from $\bar{p} - \bar{n}$ (coalescence model): in $\bar{n}$ rest frame, $K_{\bar{p}} < B$, or $|\vec{k}_{\bar{n}} - \vec{k}_{\bar{p}}| < (2m_p B)^{\frac{1}{2}} \sim p_0 \sim 70\ \mathrm{MeV} \Rightarrow \bar{D}$!
  more accurately, p_0 by fitting ALEPH Z decay data:
  $p_0 = 160\mathrm{MeV}$
- Different Spectral features for different final states–colored ($\bar{b}b$, $\bar{t}t$): hadronize in rest frame, peak at low K even at large m_{DM}–*favored by $\bar{D}$ search*; color-neutral ($h^0 h^0$, $W^+ W^-$): hadronize in boosted frame, peak at higher K esp. at high m_{DM}

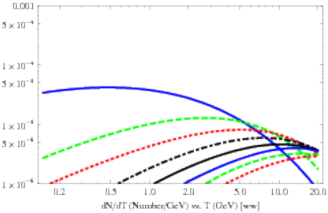

Figure: The anti-D injection spectrum as a function of Kinetic Energy, T, for W^+W^-, $hh(115\ \mathrm{GeV})$, $\bar{t}t$, $b\bar{b}$ final states. $m_{DM} =$ $100\ \mathrm{GeV(blue/solid)}$, $200\ \mathrm{GeV(green/dashed)}$, $300\ \mathrm{GeV(red/dottd)}$, $400\ \mathrm{GeV(bla}$ $500\ \mathrm{GeV(black/solid)}$, $600\ \mathrm{GeV(blue/solid)}$, $700\ \mathrm{GeV(green/dashed)}$, $800\ \mathrm{GeV(r}$

Anti-D Flux: Propagation from galactic halo to us

- 2D diffusion model. The diffusion equation for charged cosmic rays (Uncertainty in model parameters: MIN, MED, MAX):

$$\begin{aligned}\frac{d}{dt}\psi(r,z,E) &= Q(r,z,E) - 2h\delta(z)\Gamma_{ann}(E)(n_H + 4^{\frac{2}{3}} n_{He})\psi(r,z,E) \\ &+ K(E)\left(\frac{\partial^2}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r}\right)\psi(r,z,E) - V_C \frac{\partial}{\partial z}\psi(r,z,E)\end{aligned}$$

  primary source Q obtained from DM $\bar{D}$ injection spectrum ($\frac{dN}{dT}$)

$$\begin{aligned}Q(r,z,T) &= \frac{1}{2}\langle\sigma v\rangle\left(\frac{\rho(r,z)}{m_{DM}}\right)^2 \frac{dN}{dT}. \\ \rho_{Ein}(r) &= \rho_\odot \exp\left[-2\left[\left(\frac{r}{r_s}\right)^\alpha - \left(\frac{r_\odot}{r_s}\right)^\alpha\right]/\alpha\right]\end{aligned}$$

- Solar Modulation:

$$\Phi_\oplus(T_\oplus) = \frac{2mT_\oplus + T_\oplus^2}{2mT + T^2}\Phi(T), \quad T = T_\oplus + e\phi_F.$$

Experimental Reach for Certain Final States ($BR = 1, \langle \sigma v \rangle = 1\mathrm{pb}$)

Mass reach: the largest DM mass (GeV) for which the anti-D flux yields N_{crit}–number for 2σ or 5σ signal at certain experiment.

Experiment	$\bar{q}q$	$\bar{t}t$	$h^0 h^0$	$W^+ W^-$	N_{crit}
AMS-02 high (2σ)	110	$< m_t$	$< m_h$	$< m_W$	1
AMS-02 low (2σ)	150	220	150	140	1
GAPS (LDB) (2σ)	150	220	150	120	1
GAPS (ULDB) (2σ)	360	560	300	200	1
GAPS (SAT) (2σ)	700	1000	550	270	4
AMS-02 high (5σ)	50	$< m_t$	$< m_h$	$< m_W$	6
AMS-02 low (5σ)	70	$< m_t$	$< m_h$	$< m_W$	4
GAPS (LDB) (5σ)	75	$< m_t$	$< m_h$	$< m_W$	3
GAPS (ULDB) (5σ)	150	220	150	120	5
GAPS (SAT) (5σ)	360	550	300	200	14

General Bounds/Features of DM related to its detections

- Features of general DM: spin $(0, 1/2, 1)$, interaction with SM (operator), mass$\Rightarrow$
  $\Omega_{DM} \rightarrow \langle\sigma|v|\rangle_{therm} = 1\mathrm{pb}$, $\langle\sigma|v|\rangle_{ann}$ (IdDt),
  $\sigma_{SI} \lesssim 10^{-7}\mathrm{pb}$ (XENON, CDMS bound), σ_{SD} (DiDt)
  $\Rightarrow \frac{\langle\sigma|v|\rangle_{therm}}{\sigma_{SI}} \geq 10^7$
- Correlation between $\langle\sigma|v|\rangle_{therm}$ and σ_{SI} via crossing symmetry of Feynman diagram$\Rightarrow$Tension
  E.g. DM χ interacts with quarks, leptons, W/Z with 'unbiased' universal couplings, mediator couplings to DM and SM state g_1, g_2. To relate to both $\langle\sigma|v|\rangle_{therm}$ and DiDt, focus on e.g. u quark. Effective Fermi coupling for the related operator $\chi^\dagger\chi\bar{q}q$

$$G = \frac{g_1 g_2}{[(4m_\chi^2 - M^2)^2 + \Gamma_M^2 M^2]^{1/2}}$$

BR(u) for annihilation$\sim$ 10% $\Rightarrow$

$$\langle\sigma|v|\rangle^{u}_{therm} = \frac{3(g_1 g_2)^2}{4\pi[(4m_\chi^2 - M^2)^2 + \Gamma_M^2 M^2]} = 10^{-37}\mathrm{cm}^2.$$

Crossing the Feynman diagram $\Rightarrow$associated process/rate for DiDt(SI)

$$\begin{aligned}\sigma_{\chi p} &= \frac{1}{4\pi}\frac{m_p^2}{(m_\chi + m_p)^2}\frac{(g_1 g_2)^2}{M^4}\left(\sum_{q=u,d,s}\frac{m_p}{m_q}f^p_{Tq} + \sum_{q=c,b,t}\frac{m_p}{m_q}\frac{2}{27}f^p_{TG}\right)^2 \\ &\approx \frac{1}{\pi}\frac{m_p^2}{m_\chi^2}\frac{(g_1 g_2)^2}{M^4} \sim 10^{-41}\mathrm{cm}^2\end{aligned}$$

f^p_{TG}, f^p_{Tq} $\propto$gluon and quark matrix element in the nucleon
However, current DiDt bound$\Rightarrow$ $\sigma_{\chi p} \lesssim 10^{-43}\mathrm{cm}^2$ for EW mass DM $\Rightarrow$ naive estimation $\sim$ $O(100)$ real $\frac{\langle\sigma|v|\rangle_{therm}}{\sigma_{SI}}$ (more severe if null result in near future XENON100/1T...)

Realistic Models: Mechanisms Affecting $\frac{\langle\sigma|v|\rangle_{therm}}{\sigma_{SI}}$-1

- Enhance $\langle\sigma|v|\rangle_{therm}$:
  - S-Channel Resonance
  - Coannihilation with mass degenerate partner, particularly useful when self-annihilation p-wave suppressed
- Suppress SI coupling
  - Suppression from Flavor Dependent Couplings: Suppressed coupling to light quark, while other efficient channels (t, lepton, W/Z) maintains $\langle\sigma|v|\rangle_{therm}$. 'Classic' example--Yukawa coupling via h-like mediator: Go back to SI $\sigma_{\chi p}$, replace the universal g_2 by y_q:

$$\sigma_{\chi p} = \frac{1}{4\pi}\frac{m_p^2}{(m_\chi+m_p)^2}\frac{(g_1)^2}{M^4}\left(\sum_{q=u,d,s}\frac{m_p}{m_q}y_q f_{Tq}^p + \sum_{q=c,b,t}\frac{m_p}{m_q}y_q\frac{2}{27}f_{TG}^p\right)^2$$

$$\approx \frac{1}{\pi}\frac{m_p^2}{m_\chi^2}\frac{(g_1)^2}{M^4}(\frac{m_p}{v})^2\cdot 0.2 \approx 10^{-45}\mathrm{cm}^2$$

around the reach of XENON100/XENON1T, Super-CDMS!

Realistic Models: Mechanisms Affecting $\frac{\langle\sigma|v|\rangle_{therm}}{\sigma_{SI}}$-2

- - **<u>Operator dependent kinematic suppression</u>**: small transferred $p \sim \mathrm{keV} \Rightarrow \epsilon_{\mathrm{v}} = \left(\frac{\mathrm{v}_{DM}}{c}\right)^2 \sim 10^{-6}$; low p_q in nucleon:$\epsilon_{QCD} = \left(\frac{\Lambda_{QCD}}{m_{DM}}\right)^2 \sim 10^{-6}$
  - **<u>Inelastic splitting</u>**: DM has heavier 'excited' partner, inelastic scattering dominant; $\Delta m \Rightarrow$ kinematic barrier, suppressed by n_{DM} at high v. In general $\Delta m \gtrsim 1\mathrm{MeV}$ evade all DiDt bounds. Recently well known for explaining DAMA with $\Delta m \sim 100\mathrm{keV}$.
  - **<u>Annihilation to Dark Sector States</u>**: DM dominantly couples to dark sector, only via small mixing to SM. GeV-dark sector recently well explored in light of PAMELA, FERMI anomaly.
- Non-Thermal DM: axions, gravitino LSP. Mostly 'super-weakly' interacting at both DiDt and IdDt

Operator Properties Relevant for Dark Matter Detection

- Motivation: operator dependence of $\epsilon_V, \epsilon_{QCD}, \epsilon_Y$ for DiDt and p-wave/helicity suppression for IdDt
- Study general scalar, fermion (Majorana, Dirac), vector DM. All 4-point SM-DM interaction operator can be written in form of $\mathcal{O}_{DM}\mathcal{O}_{SM}$, where $\mathcal{O}$ is bilinear operator
- All interesting information (potential suppressions) easily extracted from bilinear properties and CP, J conservation. (Tables listed next page)
- Useful tool for model building, as well as systematic understanding of existing models (later...)

Fermion:

	$\bar{\Psi}\Psi$	$\bar{\Psi}\gamma^5\Psi$	$\bar{\Psi}\gamma^\mu\Psi$	$\bar{\Psi}\gamma^\mu\gamma^5\Psi$	$\bar{\Psi}\sigma^{\mu\nu}\Psi$	$\bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi$	$(\bar{\Psi}\gamma^\mu\partial^\nu\Psi)_\pm$	$(\bar{\Psi}\gamma^\mu\gamma^5\partial^\nu\Psi)_\pm$
SI	ϵ_Y	0	✓	$\epsilon_{\rm v}$	$\epsilon_{\rm v}$	$\epsilon_{\rm v}$	ϵ_{QCD}	$\epsilon_{\rm v}$
SD	0	$\epsilon_{\rm v}\epsilon_Y$	$\epsilon_{\rm v}$	✓	✓	✓	$\epsilon_{\rm v}$	ϵ_{QCD}
C	$+$	$+$	$-$	$+$	$-$	$-$	$\mp$	$\pm$
P	$+$	$-$	$(-)^\mu$	$-(-)^\mu$	$(-)^{\mu,\nu}$	$-(-)^{\mu,\nu}$	$(-)^{\mu,\nu}$	$-(-)^{\mu,\nu}$
s-wave	0	✓	✓	✓	✓	✓	$+$: ✓ , $-$: 0	$+$: 0, $-$: ✓

Scalar:

	$\phi^\dagger\phi$	$(\phi^\dagger\partial_\mu\phi)_\pm$	$(\phi^\dagger\partial_\mu\partial_\nu\phi)_\pm$
C	$+$	$\pm$	$\pm$
P	$+$	$(-)^\mu$	$(-)^{\mu,\nu}$
s-wave	✓	$+$: ✓ , $-$: 0	$+$: ✓ , $-$: 0

Vector boson:

	VV	$(VV)^{\mu\nu}_\pm$	$(\epsilon VV)^{\mu\nu}_\pm$	$(V\partial V)^\mu_\pm$	$(\epsilon V\partial V)^\mu_\pm$	$(V\partial\partial V)^{\mu\nu}_\pm$	$(\epsilon V\partial\partial V)^{\mu\nu}_\pm$	$(V\partial^2 V)_\pm$
C	$+$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
P	$+$	$(-)^{\mu,\nu}$	$-(-)^{\mu,\nu}$	$(-)^\mu$	$-(-)^\mu$	$(-)^{\mu,\nu}$	$-(-)^{\mu,\nu}$	$+$
s-wave	✓	✓	✓	$+$: ✓ , $-$: 0				

Anti-D detection prospect for specific models

Predicted number of anti-deuterons detected in various experiments for a set of dark matter models. Promising at GAPS -ULDB, SAT

Model	m_{DM} (GeV)	$\sigma\lvert v\rvert$	ξ_W	ξ_q	ξ_t	ξ_h	$N_{2\sigma}=1$ $N_{5\sigma}=4$ (ULDB)	$N_{2\sigma}=5$ $N_{5\sigma}=14$ (SAT)	σ_{SI}	σ_{SD}
SUSY F.P (1)	190	0.67	0.2	0.02	0.73	0	4	47	10^{-8}	10^{-4}
SUSY F.P (2)	772	0.33	0.55	0	0.38	0	0	1	10^{-8}	10^{-5}
SUSY coann	148	0.17	0	1	0	0	1	11	10^{-8}	10^{-6}
SUSY A-funnel	163	0.6	0	0.92	0	0	2	30	10^{-8}	10^{-6}
UED $B^{(1)}$	900	0.6	0	0.19	0.16	0.02	0	0	10^{-8}	10^{-6}
UED $B^{(1)}$ coann.	600	0.6	0	0.19	0.16	0.02	0	1	10^{-8}	10^{-6}
LHTP	200	0.8	1	0	0	0	0	9	10^{-12}	10^{-10}
LZP ν_R^0	300	1	0.06	0	0.94	0	3	38	10^{-9}	10^{-7}
Singlet (scalar)	200	1	0	0	0	1	2	33	10^{-8}	0
Doublet/Singlet	75	0.1	1	0	0	0	3	46	0	10^{-4}

Conclusions

- Anti-D is a **unique low background IdDt channel** for DM
- With current day $\langle\sigma|v|\rangle_{ann} = 1\ \mathrm{pb}$, near future experiments (AMS-02, 3-phase of GAPS) have good reach for various annihilation final states
- General tension between $\langle\sigma|v|\rangle_{therm}$ and bound on σ_{SI} is studied, basic mechanisms listed as solution. Operator analysis for various DM/interaction: for a variety of models significant $\bar{D}$ signal even when DiDt rate highly suppressed
- Detection prospects for various well-motivated models is studied: promising at GAPS-ULDB, SAT